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(54) **POWER CONVERSION SYSTEM AND FILTER THEREFOR**

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H02P 27/08 (2006.01)
H02M 7/00 (2006.01)

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(58) **Field of Classification Search**

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See application file for complete search history.

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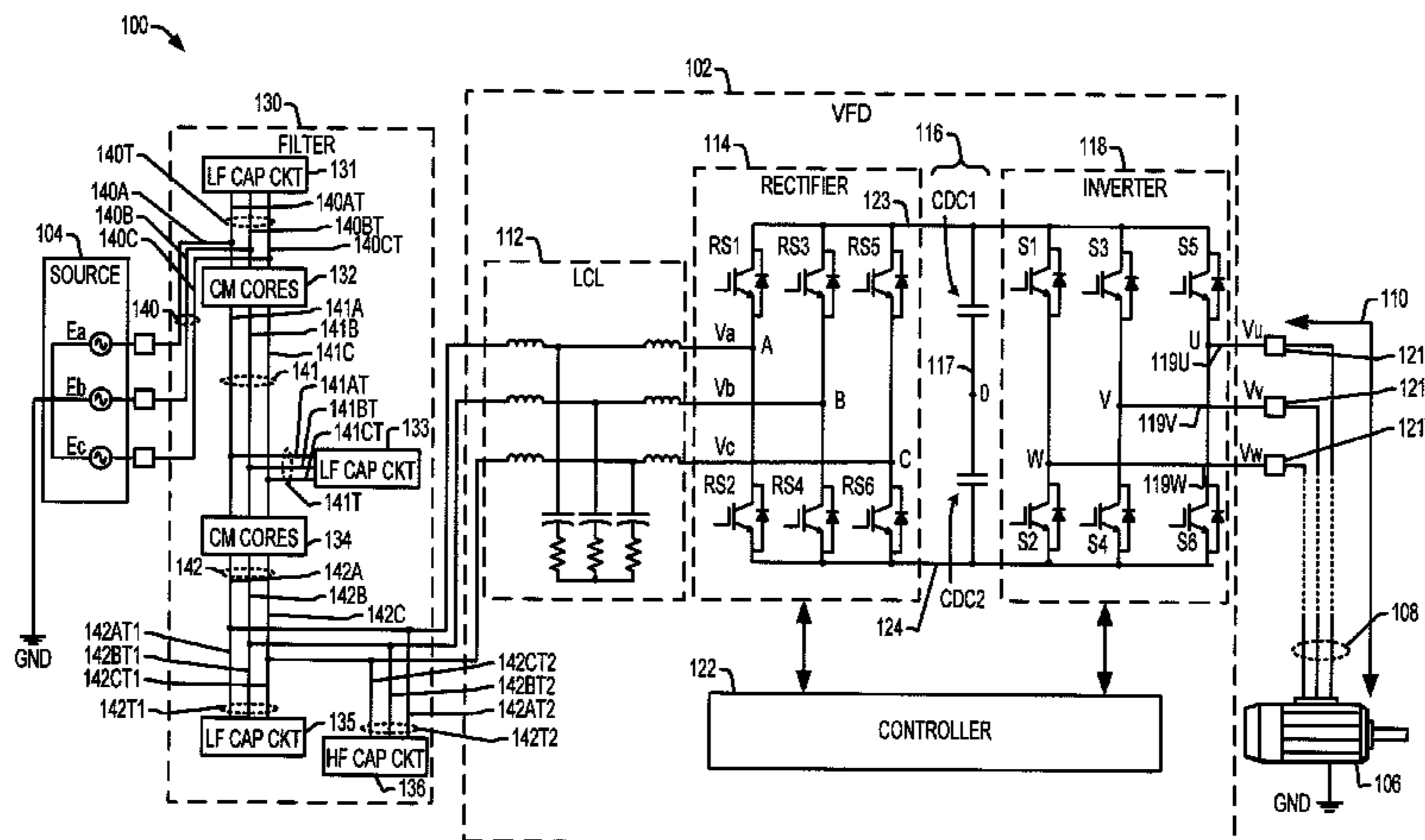
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(57) **ABSTRACT**

Power conversion systems and filters therefor include conductive busbars, a first low frequency capacitor circuit coupled with the busbars at a first location proximate a filter input, a first inductor circuit with common mode cores extending around the busbars at a second location between the first location and a filter output, a second low frequency capacitor circuit coupled with the busbars at a third location between the second location and the filter output, a second inductor circuit with second common mode cores extending around the busbars at a fourth location between the third location and the filter output, a third low-frequency capacitor circuit coupled with the busbars at a fifth location between the fourth location and the filter output, and a high frequency fourth capacitor circuit, coupled with one of the busbars at the fifth location.

20 Claims, 7 Drawing Sheets



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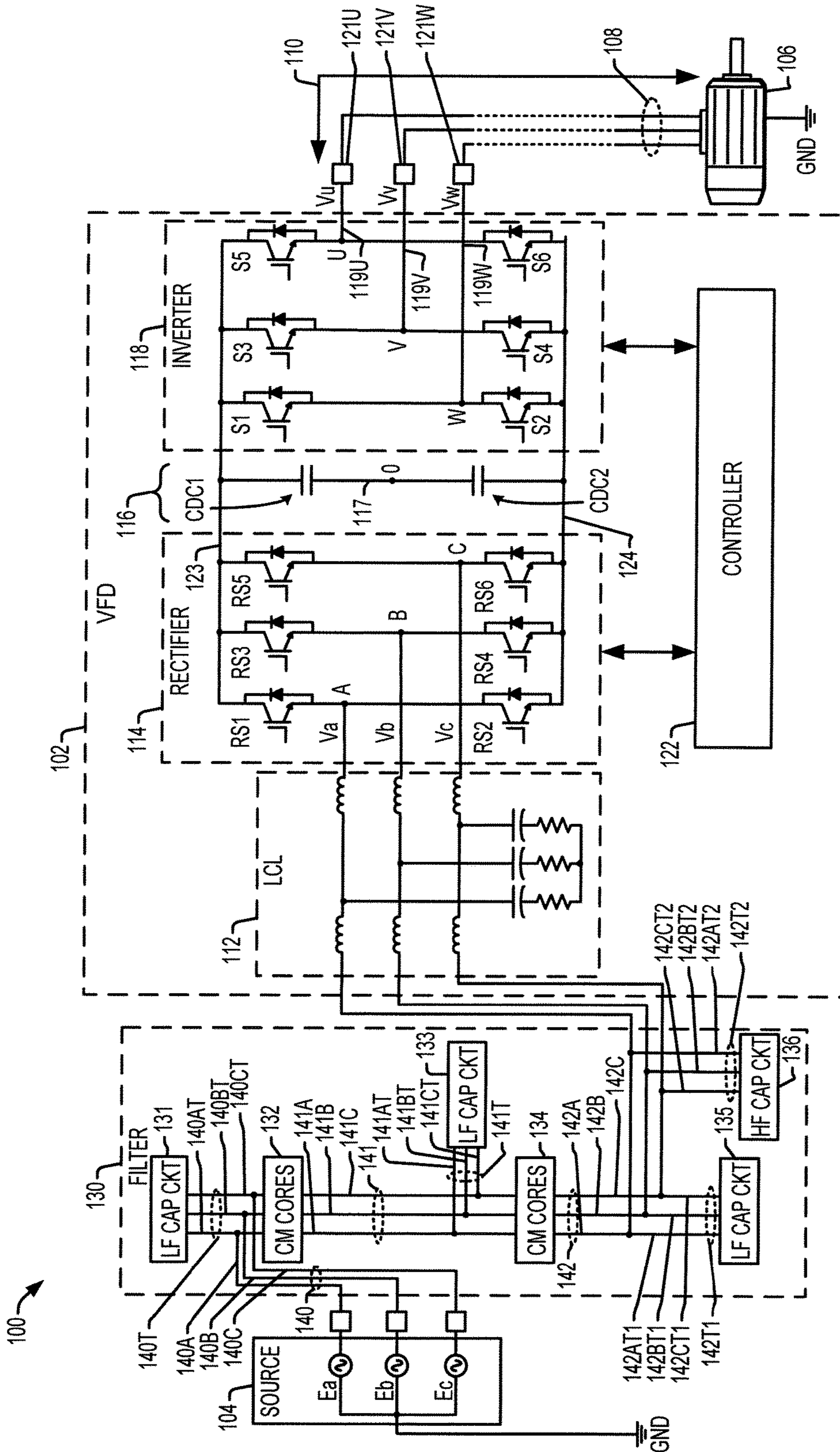


FIG. 1

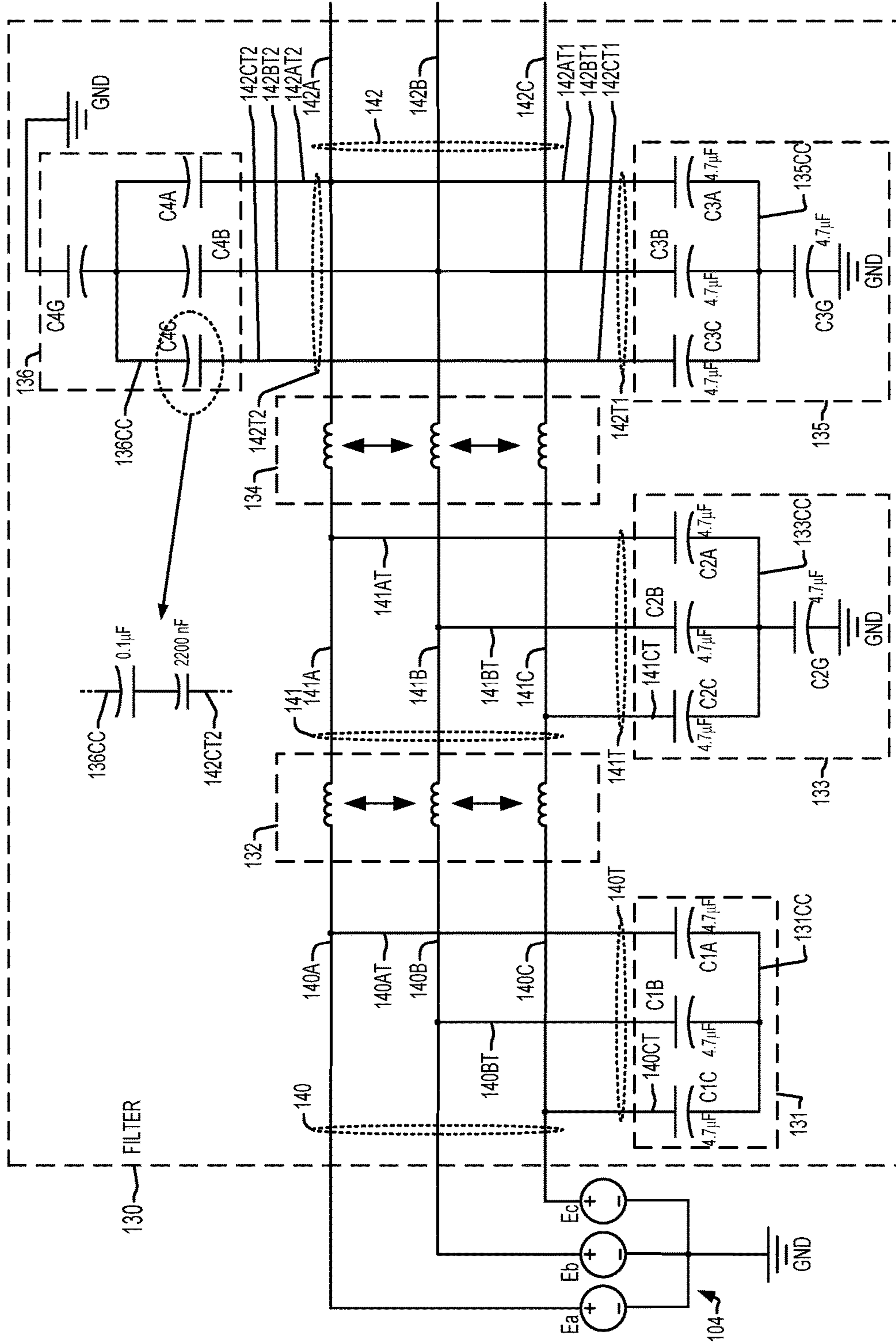


FIG. 2

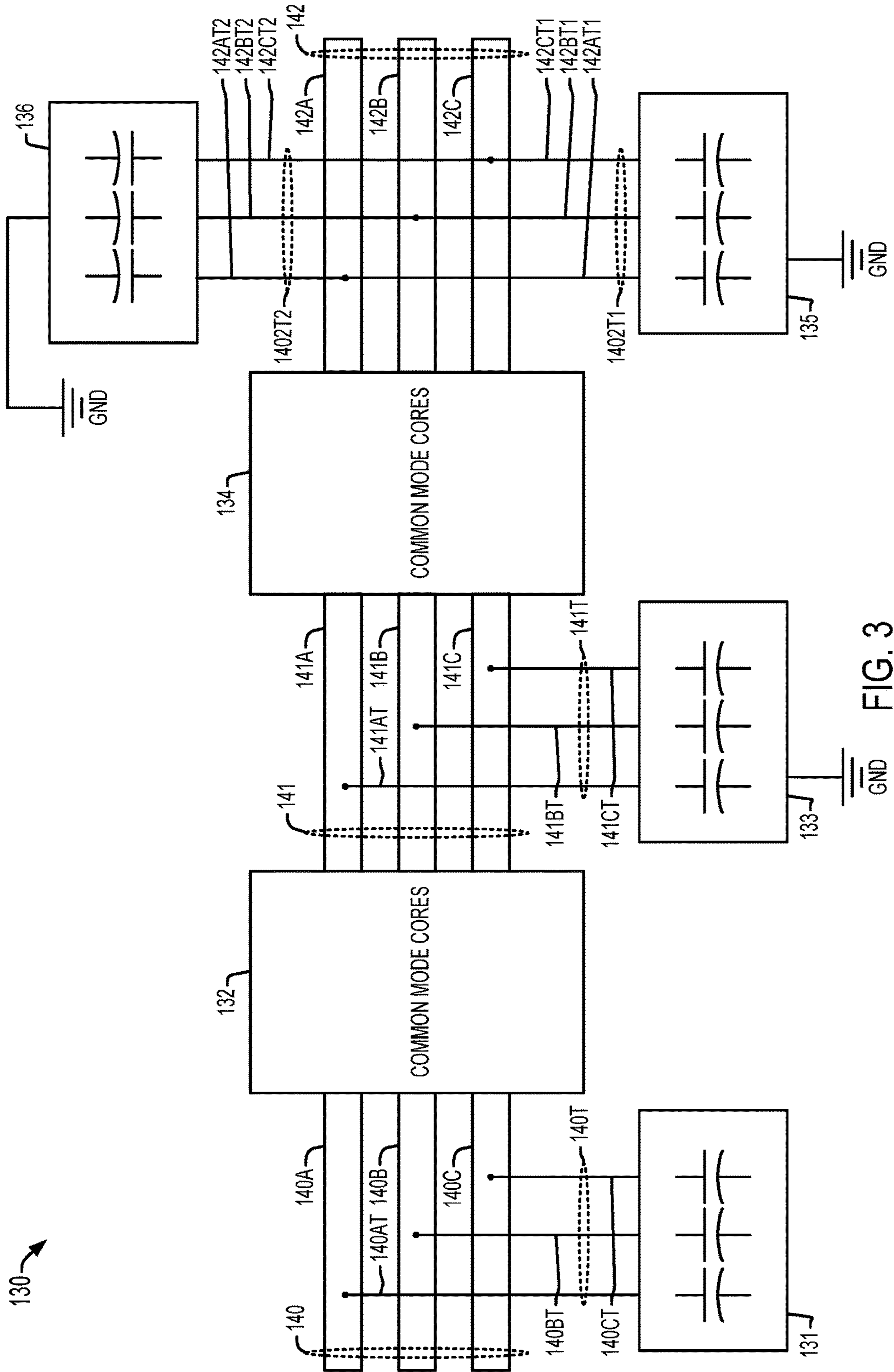


FIG. 3

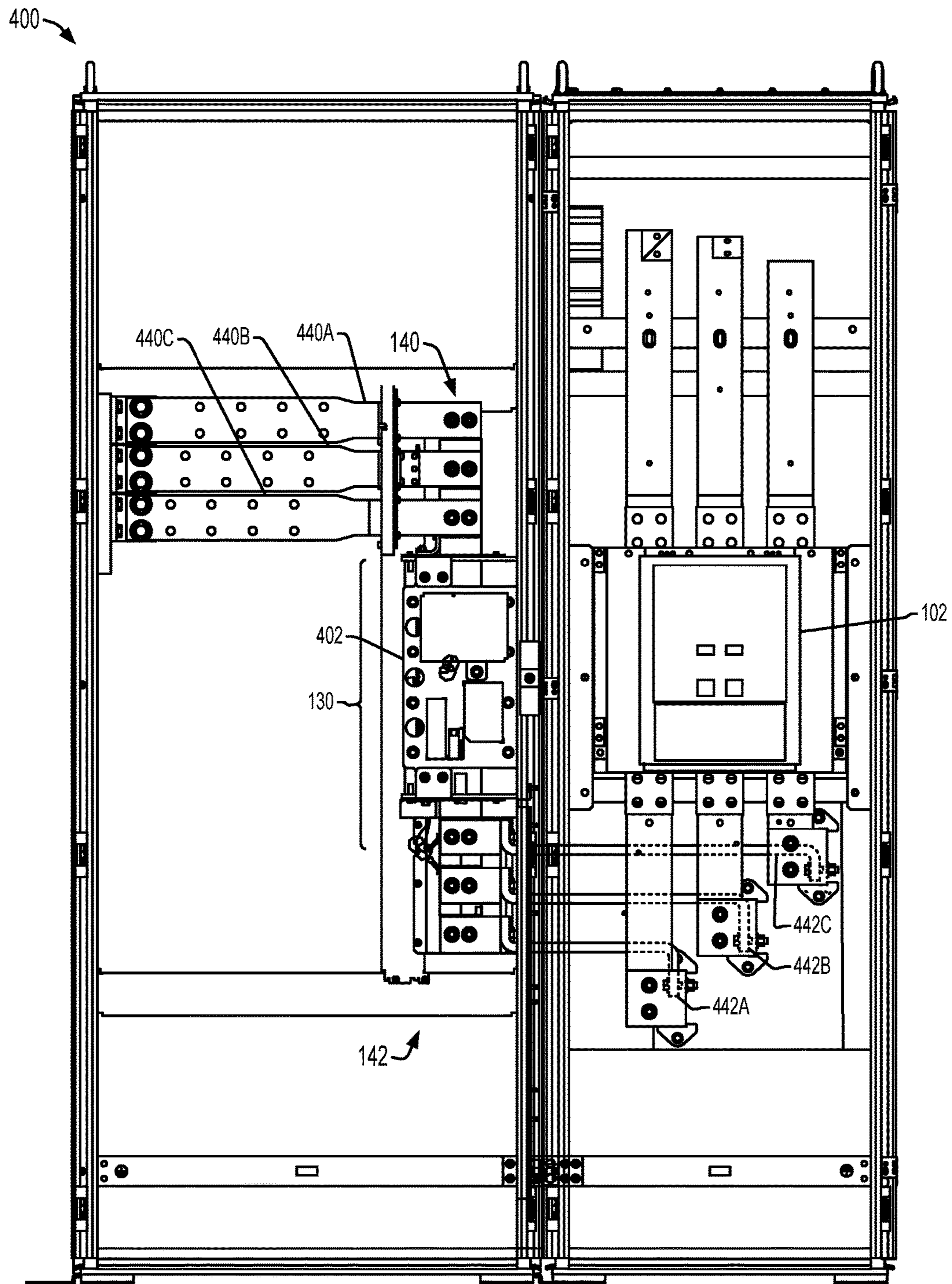


FIG. 4

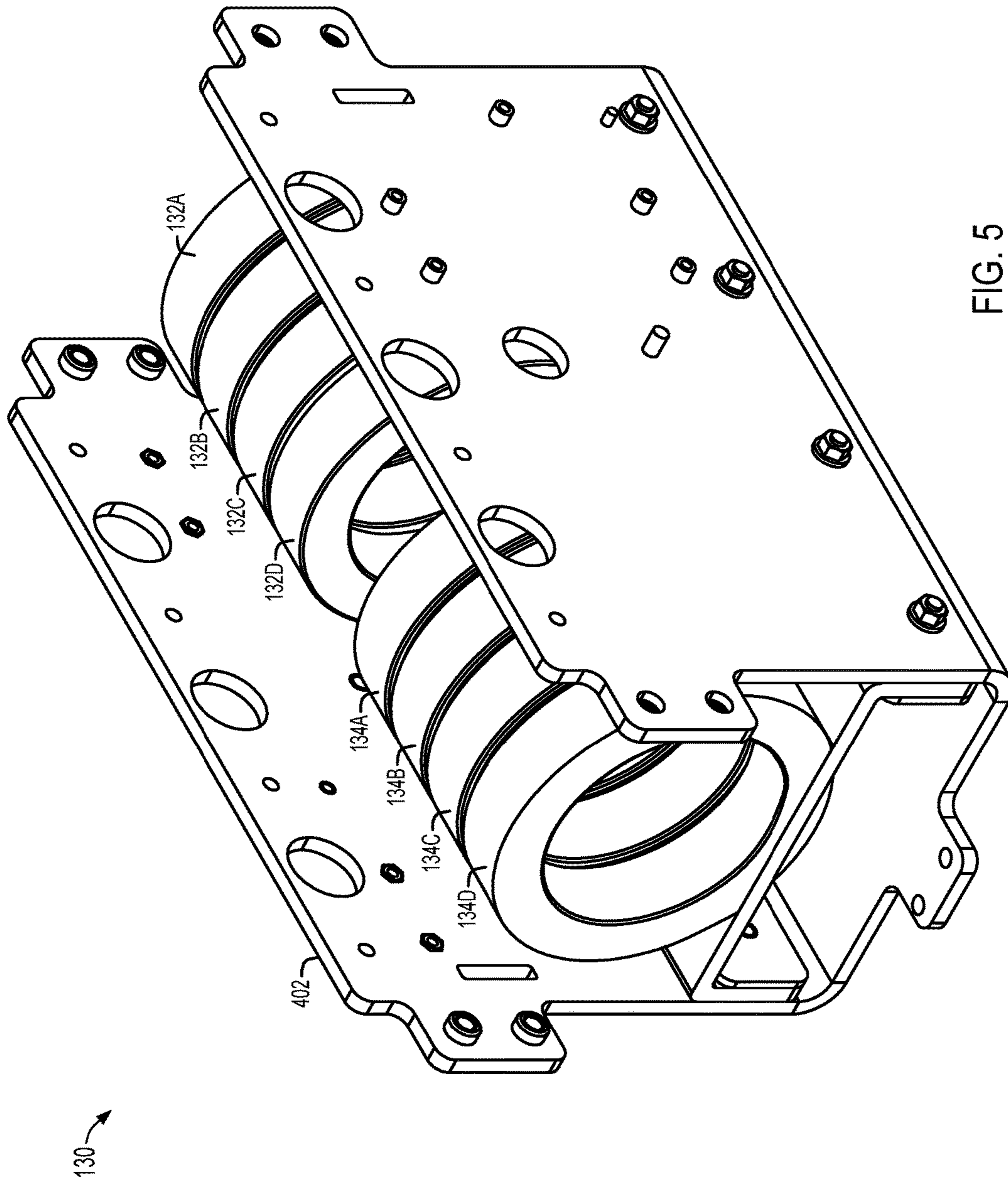


FIG. 5

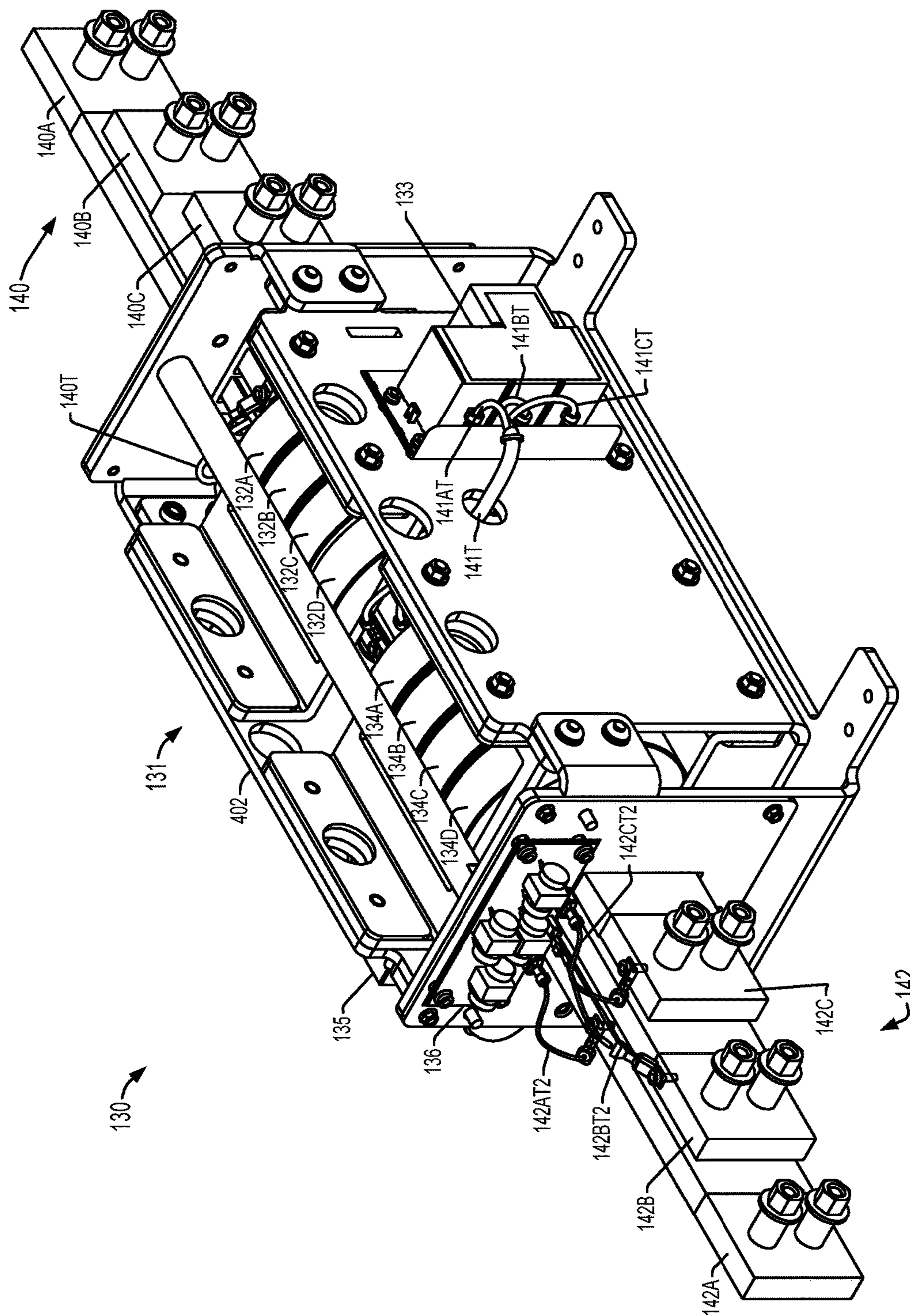


FIG. 6

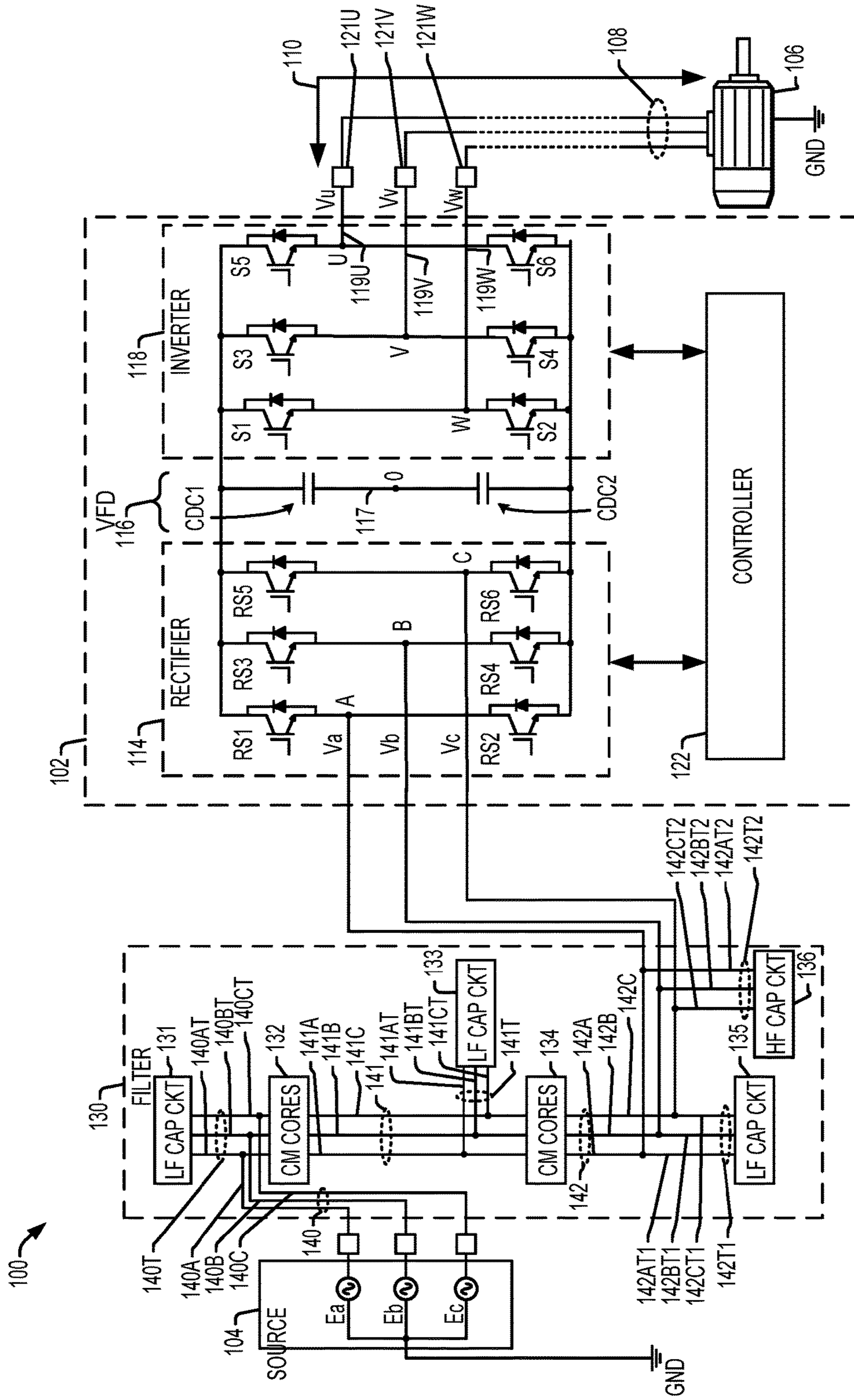


FIG. 7

POWER CONVERSION SYSTEM AND FILTER THEREFOR

BACKGROUND INFORMATION

The subject matter disclosed herein relates to power conversion.

BRIEF DESCRIPTION

Various aspects of the present disclosure are now summarized to facilitate a basic understanding of the disclosure, wherein this summary is not an extensive overview of the disclosure, and is intended neither to identify certain elements of the disclosure, nor to delineate the scope thereof. Rather, the primary purpose of this summary is to present the concept of the disclosure in a simplified form prior to the more detailed description that is presented hereinafter. The present disclosure provides power conversion systems and filters therefor. The filter includes conductive busbars, a first low frequency capacitor circuit coupled with the busbars at a first location proximate a filter input, a first inductor circuit with common mode cores extending around the busbars at a second location between the first location and a filter output, a second low frequency capacitor circuit coupled with the busbars at a third location between the second location and the filter output, a second inductor circuit with second common mode cores extending around the busbars at a fourth location between the third location and the filter output, a third low-frequency capacitor circuit coupled with the busbars at a fifth location between the fourth location and the filter output, and a high frequency fourth capacitor circuit, coupled with one of the busbars at the fifth location.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram.
FIG. 2 is a schematic diagram.
FIG. 3 is a schematic diagram.
FIG. 4 is a side elevation view.
FIG. 5 is a perspective view.
FIG. 6 is a perspective view.
FIG. 7 is a schematic diagram.

DETAILED DESCRIPTION

Referring now to the figures, several embodiments or implementations are hereinafter described in conjunction with the drawings, wherein like reference numerals are used to refer to like elements throughout, and wherein the various features are not necessarily drawn to scale. In the following discussion and in the claims, the terms “including”, “includes”, “having”, “has”, “with”, or variants thereof are intended to be inclusive in a manner similar to the term “comprising”, and thus should be interpreted to mean “including, but not limited to . . .” Also, the term “couple” or “couples” is intended to include indirect or direct electrical or mechanical connection or combinations thereof. For example, if a first device couples to or is coupled with a second device, that connection may be through a direct electrical connection, or through an indirect electrical connection via one or more intervening devices and connections.

FIG. 1 shows an example industrial power conversion system 100 with a motor drive 102 that receives and converts AC electrical input power from a source 104 to drive a motor load 106 through a motor cable 108 having a

cable length 110. The example AC input and output of the converter 102 are three phase configurations. Other implementations are possible using any combination of single or multiphase inputs and outputs to drive a motor 106 or other type of load. The example motor drive 102 is a voltage source converter (VSC) motor drive, which includes an input filter 112, a rectifier 114, a DC bus circuit 116 with DC bus capacitors CDC1 and CDC2 that define a center node 117 (e.g., zero volts). The DC bus voltage of the bus circuit 116 drives an inverter 118 with an inverter output 119 (e.g., output phase lines 119U, 119V and 119W) connected to output terminals 121U, 121V and 121W to drive a load 106 through the cable 108. The motor drive 102 also includes a controller or control circuit 122 to provide switching control signals to the inverter 118, as well as rectifier switching control signals to an active front end (AFE) implementation of the rectifier 114 as shown in FIG. 1. In certain examples, an output filter and/or an output transistor (not shown) can be connected between the inverter output 119 and the motor cable 108, for example, to drive a motor load 106 through a cable 108 having a long length 110 four electronic submersible pump (ESP) applications. The DC bus circuit 116 includes a first DC power path or node 123, and a second DC power path or node 124.

The rectifier 114 includes a rectifier input A, B, C configured to receive a rectifier AC input signal Va, Vb, Vc, as well as a rectifier output configured to provide the DC voltage output signal to the DC bus circuit 116. In the illustrated example, the rectifier 114 is an active rectifier with rectifier switching devices RS1-RS6 coupled between the rectifier input A, B, C and the rectifier output. In other examples, a passive rectifier can be used (not shown). The power conversion system 100 also includes a filter 130 coupled between the source 104 and the motor drive 102. In the example of FIG. 1, the filter 112 operates as a second input filter connected between the filter output 142 and the rectifier input A, B, C, and which includes phase-specific L-C-L (inductor-capacitor-inductor) circuit components. In other implementations (e.g., FIG. 7 below) the second filter 112 can be omitted. The example three phase AC power source 104 provides AC phase voltage signals Ea, Eb and Ec through the filter 130 to the inputs of the input second filter 112, and the second filter 112 provides filtered AC input voltage signals Va, Vb and Vc to the respective phase input lines A, B and C of the rectifier 114. In one implementation (e.g., FIG. 4 below), the motor drive 102 includes a housing that encloses the second filter 112, the active rectifier 114, the DC bus circuit 116 at the inverter 118, along with the controller 122. In certain implementations, moreover, the filter 130 is housed within a multi-cabinet enclosure, and can be installed as an ad-on component to an existing cabinet-mounted motor drive (e.g., FIG. 4 below).

The filter 130 advantageously reduces or mitigates electromagnetic interference (EMI) emissions from the switching operation of the active front and rectifier 114 and/or the switching inverter 118, to protect the power source 104 against excessive EMI. In one example, the switching rectifier 114 and the inverter 118 operate at pulse width modulation (PWM) switching frequencies of several hundred hertz up to several kilohertz. In one example, the second filter 112 (when included) is designed to reduce or filter out all or at least a portion of the frequency content in the range of the pulse width modulation switching frequencies of the rectifier 114 and/or the inverter 118. The inverter 118 includes a DC input coupled with the DC bus circuit 116, and a plurality of inverter switching devices S1-S6 coupled between the DC input and the inverter output 119. The

inverter switches S1-S6 are configured to operate according to inverter switching control signals from the controller 122 in order to provide an inverter output signal Vu, Vv, Vw at the inverter output 119 to directly or indirectly drive the load 106.

The inverter 118 switching devices S1-S6 are individually coupled between a corresponding one of the DC current paths 123 or 124 of the intermediate DC circuit 116 and a corresponding one of the AC output nodes 119U, 119V or 119W (also labelled U, V, and W in FIG. 1). The inverter switching devices S1-S6 are individually operative according to corresponding inverter switching control signals from the controller 122 in order to selectively electrically couple the corresponding DC current path with the corresponding AC output node. The controller 122 provides the inverter switching control signals in order to cause the inverter 118 to generate a controlled amplitude and frequency of the single or multiphase AC output signal used to drive a motor load 106. In this manner, the controller 122 can implement a variety of different motor control functions, including speed control, torque control, etc.

The rectifier 114 can be a passive rectifier including one or more diode rectifier components, or may be an active front end (AFE) system with one or more rectifier switching devices RS1, RS2, RS3, RS4, RS5 and RS6 (e.g., IGBTs, etc.). The example active rectifier switches RS1-RS6 are configured to operate according to rectifier switching control signals from the controller 122 to convert input AC electrical power to provide the DC bus voltage in the DC bus circuit 116. The rectifier switching devices RS1-RS6 are individually coupled between a corresponding one of the rectifier input nodes A, B, or C and a corresponding one of the first and second DC output nodes 123 or 124. In operation, the rectifier switching devices RS1-RS6 individually operate according to a corresponding rectifier switching control signal to selectively couple a corresponding rectifier input node A, B, or C with a corresponding DC output node 123 or 124 according to a corresponding rectifier switching control signal from the controller 122. The controller 122 provides the rectifier switching control signals in order to control conversion of AC input power received by the rectifier 114 into a controlled or regulated DC bus voltage in the DC bus circuit 116.

The illustrated motor drive 102 is a voltage source converter configuration including one or more capacitive storage elements in the DC bus circuit 116. The DC bus circuit 116 may include a single capacitor CDC or multiple capacitors (e.g., CDC1 and CDC2 in FIG. 1) connected in any suitable series, parallel and/or series/parallel configuration to provide a DC bus capacitance across the inverter input terminals. The intermediate DC bus circuit 116 in one example includes first DC current path 123 coupled with the first DC output node of the rectifier 114, and a second DC current path 124 coupled with the second DC output node of the rectifier 114.

The controller 122 in one example includes a processor and an associated electronic memory (not shown in FIG. 1) which stores program instructions to implement a closed loop control program to regulate or control one or more of voltage, current, speed, torque, etc. The controller 122 in certain embodiments implements a motor speed and/or position and/or torque control scheme in which the controller 122 selectively provides the switching control signals to the inverter switches S1-S6 in a closed and/or open-loop fashion according to one or more setpoint values such as a motor speed setpoint. The setpoint in one example is a signal or value generated by the controller 122, or a fixed setpoint

value, or such setpoint value can be received from an external system (not shown). In practice, the motor drive 102 may also receive a torque setpoint and/or a position (e.g., angle) setpoint, and such desired signals or values (setpoint(s)) may be received from a user interface and/or from an external device such as a distributed control system, etc. (not shown). As used herein, a signal can be an analog signal, such as a current or a voltage signal, or a signal can include digital values generated or consumed by the controller 122.

Referring also to FIGS. 2-6, the filter 130 in the illustrated three phase example includes a filter input 140 with three filter input terminals 140A, 140B, and 140C, as well as a filter output 142 with three filter output terminals 142A, 142B, and 142C coupled with the rectifier input A, B, and C, respectively. FIG. 2 shows a schematic diagram of the example 3 phase filter 130 connected to the source 104. FIG. 3 is a partial schematic representation of the filter 130, including conductive bus bars that extend from a first end (e.g., on the left in FIG. 3) to a second end (e.g., on the right in FIG. 3).

The filter 130 includes three conductive busbars individually including the first end connected to a corresponding one of the filter input terminals 140A, 140B, and 140C, and the second end connected to a corresponding one of the three filter output terminals 142A, 142B, and 142C. In one example, the busbars are individually continuous conductive structures (e.g., metal) that extend between the first and second ends, with different locations along the lengths of the busbars as described further below. The example filter 130 includes a cascade of circuits configured along the lengths of the busbars, including a first capacitor circuit 131 followed by a first inductor circuit 132, a second capacitor circuit 133 followed by a second inductor circuit 134, and third and fourth capacitor circuits connected to the second ends of the busbars.

As best shown in FIGS. 2 and 3, the example three phase filter 130 includes a first capacitor circuit 131 with three first capacitors C1A, C1B, and C1C individually coupled in a Y-circuit between a first common connection 131CC and a corresponding one of the busbars at a first location proximate the filter input terminals 140A, 140B, and 140C. The first capacitors C1A, C1B, and C1C of the first capacitor circuit 131 are respectively connected with the corresponding busbars by tap connections 140AT, 140BT, and 140CT (collectively 140T). In one example, as shown in FIG. 6 below, the tap connections 140T, and the other tap connections of further capacitor circuits in the filter 130, include short wires to facilitate reduced parasitics and to enhance high-frequency (e.g., EMI) frequency reduction by the filter 130.

The filter 130 further includes a first inductor circuit 132 with first common mode cores 132A, 132B, 132C, and 132D that individually extend around (e.g., encircle) the busbars at a second location between the first location and the second end of the busbars. The second capacitor circuit 133 includes second capacitors C2A, C2B, and C2C individually coupled between a second common connection 133CC and a corresponding one of the busbars at a third location 141 between the second location and the second end of the busbars. The second capacitors C2A, C2B, and C2C of the second capacitor circuit 133 are respectively connected with the corresponding busbars by tap connections 141AT, 141BT, and 141CT (collectively 141T).

The second inductor circuit 134 includes second common mode cores 134A, 134B, 134C, and 134D that individually extend around the busbars at a fourth location between the

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third location and the second end of the busbars. In one example, the first common mode cores **132A**, **132B**, **132C**, and **132D** and the second common mode cores **134A**, **134B**, **134C**, and **134D** include a nanocrystalline material. Suitable examples include soft magnetic cores T60006-L2102-W468-07—available from VAC Vacuumschmelze (e.g., Vacuumschmelze nano-crystalline Vitroperm common mode cores).

The third capacitor circuit **135** includes a plurality of third capacitors **C3A**, **C3B**, and **C3C** that are individually coupled between a third common connection **135CC** and a corresponding one of the busbars at a fifth location between the fourth location and the second end of the busbars. The third capacitors **C3A**, **C3B**, and **C3C** of the third capacitor circuit **135** are respectively connected with the corresponding busbars by tap connections **142AT1**, **142BT1**, and **142CT1** (collectively **142T1**).

The fourth capacitor circuit **136** includes fourth capacitors **C4A**, **C4B**, and **C4C** that are individually coupled between a fourth common connection **136CC** and a corresponding one of the busbars at the fifth location. In the illustrated example, the second, third, and fourth common connections **133CC**, **135CC**, and **136CC** are each coupled to a common reference node GND, although not required of all possible implementations. The fourth capacitors **C4A**, **C4B**, and **C4C** of the fourth capacitor circuit **136** are respectively connected with the corresponding busbars by tap connections **142AT2**, **142BT2**, and **142CT2** (collectively **142T2**).

As shown in FIGS. 2 and 3, the second capacitor circuit **133** includes a second grounding capacitor **C2G** connected between the second common connection **133CC** and the common reference node GND. The third capacitor circuit **135** includes a third grounding capacitor **C3G** connected between the third common connection **135CC** and the common reference node GND, and the fourth capacitor circuit **136** includes a fourth grounding capacitor **C4G** connected between the fourth common connection **136CC** and the common reference node GND.

In the illustrated filter **130**, the first, second and third capacitor circuits **131**, **133**, and **135** are low-frequency capacitor circuits, implemented as capacitor circuit boards connected by the corresponding taps to the busbars. In this example, the fourth capacitor circuit **136** is a high frequency capacitor circuit implemented as a high frequency capacitor circuit board connected by corresponding tap wires to the second ends **142** of the busbars. In one example, the first capacitor circuit **131**, the first inductor circuit **132**, the second capacitor circuit **133**, the second inductor circuit **134**, and the third capacitor circuit **135** form a band stop filter with a cut-in frequency of 150 kHz or less, and a cut-off frequency of 3 MHz to 10 MHz. In this example, the fourth capacitor circuit **136** forms a low pass filter with a cutoff frequency of 3 MHz to 10 MHz. In one example, the first capacitors **C1A**, **C1B**, **C1C**, the second capacitors **C2A**, **C2B**, **C2C**, and the third capacitors **C3A**, **C3B**, **C3C** have capacitance values of 4.7 μF , and the individual fourth capacitors **C4A**, **C4B**, **C4C** each include a 0.1 μF capacitor connected in series with a 2200 nF capacitor (as schematically shown in FIG. 2). Other component values can be used and tailored, in combination with inductance values of the inductor circuits **132** and **134**, in order to achieve a desired filter performance for the system **100**.

In operation, the filter **130** attenuates EMI and other high frequency components above the range of the PWM switching frequencies of the switching rectifier **114** and the inverter **118**. In the example of FIG. 1, the second filter **112** is designed to attenuate frequency content at or near the PWM

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switching frequencies of the rectifier **114** and the inverter **118**. In combination with the filter **130**, the filter system of FIG. 1 advantageously protects the source **104** (e.g., and any associated grid connections) from EMI and PWM switching frequency content associated with the power conversion system **100**. FIG. 7 shows another example in which the second filter **112** is omitted.

FIG. 4 shows a front view of an example implementation, including an enclosure **14** with multiple cabinets, two of which are illustrated in the drawing. This example includes a first cabinet (on the right in FIG. 4) that houses the motor drive **102** including the rectifier **114** and the inverter **118** (and any included second filter **112**). The example of FIG. 4 also includes a second cabinet (on the right) that houses the filter **130**. The filter **130** includes an aluminum frame **402** as shown in FIG. 4. In this example, input power (e.g., from the source **104** in FIG. 1) is provided along three horizontally extending busbars (labeled **440A**, **440B**, and **440C**) connected to the three busbars at the input **140** of the filter **130**. Power flows downward through the filter **130** to the filter output **142**. The busbars of the filter **130** are connected at the output **142** to horizontal busbars (labeled **442A**, **442B** and **442C**) to transition from the second cabinet to the first cabinet. In the first cabinet, the filter outputs are coupled to vertical busbars (not labeled in FIG. 4) that provide an input to the motor drive **102** (e.g., three phase inputs to the rectifier **114** directly as shown in FIG. 7 or through any included second filter **112** as schematically shown in FIG. 1).

FIG. 5 illustrates location of the first common mode cores **132A**, **132B**, **132C**, and **132D** and the second common mode cores **134A**, **134B**, **134C**, and **134D** within the frame **402** prior to installation encircling the busbars of the filter **130**. FIG. 6 illustrates the assembled filter assembly **130**, including the busbars that extend from the filter input **140** (upper right in FIG. 6) to the filter output **142** (lower left in FIG. 6). The perspective view of FIG. 6 illustrates portions of wired tap connections, including the first wired tap connection **140** of the first capacitor circuit **131** (e.g., a circuit board mounted on the back of the frame **402**, out of view in FIG. 6) to the first location along the busbars. The second capacitor circuit board **133** is shown on the front side of the frame **402** in FIG. 6, including the tap connections collectively denoted **141T**, including three individual tap connection wires **141AT**, **141BT**, and **141CT**. The third tap connection from the third capacitor circuit **135** (on the back side of the frame **402**) is not shown in the perspective view of FIG. 6. The high-frequency fourth capacitor circuit **136** is shown mounted to the end of the frame **402** in FIG. 6, including short tap wire connections **142AT2**, **142BT2**, and **142CT2**. The use of short tap wires in the filter **130** facilitates reduced parasitic inductances in the filter. Moreover, as shown in FIG. 4, the construction of the filter **130** allows easy installation into existing cabinet-mounted power conversion systems, for example, to retrofit existing installations for improved EMI performance.

Prior to the innovations of the present disclosure, EMI issues were either left unaddressed, particularly for high power motor drive systems (e.g., 650 hp-1800 hp), or required custom-designed filters and associated custom mounting features. Disclosed examples provide a compact solution including a filter **130** for reducing common mode emissions with various advantages, including compact size with a small footprint, the ability to add a filter as needed without occupying space within the motor drive **102** itself, and the ease of retrofit for existing motor drive installations. Specific examples can be designed to reduce conducted emissions to meet IEC 61800-3 category C2 limits or other

specifications for a given application. The disclosed examples facilitate reduced EMI conducted emission levels which are particularly useful in environments which have strict limits on EMI.

In the preceding specification, various embodiments have been described with reference to the accompanying drawings. It will be evident that various modifications and changes may be made thereto, and additional embodiments may be implemented, without departing from the broader scope of the invention as set forth in the claims that follow. The specification and drawings are accordingly to be regarded in an illustrative rather than restrictive sense.

The following is claimed:

1. A power conversion system, comprising:
 - a rectifier, including a rectifier input configured to receive a rectifier AC input signal, and a rectifier output configured to provide a DC output signal to a DC bus circuit;
 - an inverter, including a DC input coupled with the DC bus circuit, an inverter output, and a plurality of inverter switching devices coupled between the DC input and the inverter output and configured to provide an inverter output signal at the inverter output to directly or indirectly drive a load; and
 - a filter, including:
 - a filter input, including a plurality of filter input terminals,
 - a filter output, including a plurality of filter output terminals coupled with the rectifier input,
 - a plurality of conductive busbars individually including a first end connected to a corresponding one of the plurality of filter input terminals, and a second end connected to a corresponding one of the plurality of filter output terminals,
 - a first capacitor circuit, including a plurality of first capacitors individually coupled between a first common connection and a corresponding one of the busbars at a first location proximate the plurality of filter input terminals,
 - a first inductor circuit, including a plurality of first common mode cores that individually extend around the plurality of busbars at a second location between the first location and the second end of the busbars,
 - a second capacitor circuit, including a plurality of second capacitors individually coupled between a second common connection and a corresponding one of the busbars at a third location between the second location and the second end of the busbars,
 - a second inductor circuit, including a plurality of second common mode cores that individually extend around the busbars at a fourth location between the third location and the second end of the busbars,
 - a third capacitor circuit, including a plurality of third capacitors individually coupled between a third common connection and a corresponding one of the busbars at a fifth location between the fourth location and the second end of the busbars, and
 - a fourth capacitor circuit, including a plurality of fourth capacitors individually coupled between a fourth common connection and a corresponding one of the busbars at the fifth location.
2. The power conversion system of claim 1, wherein the rectifier is an active rectifier that further includes a plurality of rectifier switching devices coupled between the rectifier input and the rectifier output.

3. The power conversion system of claim 1, further comprising a second filter connected between the filter output and the rectifier input.

4. The power conversion system of claim 1, wherein the second, third, and fourth common connections are each coupled to a common reference node.

5. The power conversion system of claim 4, wherein the second capacitor circuit includes a second grounding capacitor connected between the second common connection and the common reference node; wherein the third capacitor circuit includes a third grounding capacitor connected between the third common connection and the common reference node; and wherein the fourth capacitor circuit includes a fourth grounding capacitor connected between the fourth common connection and the common reference node.

6. The power conversion system of claim 1, wherein the first common mode cores and the second common mode cores include a nanocrystalline material.

7. The power conversion system of claim 1, wherein the first capacitor circuit, the first inductor circuit, the second capacitor circuit, the second inductor circuit, and the third capacitor circuit form a band stop filter with a cut-in frequency of 150 kHz or less, and a cut-off frequency of 3 MHz to 10 MHz; and wherein the fourth capacitor circuit forms a low pass filter with a cutoff frequency of 3 MHz to 10 MHz.

8. The power conversion system of claim 7, wherein the first capacitors, the second capacitors, and the third capacitors have capacitance values of 4.7 μ F.

9. The power conversion system of claim 8, wherein the individual fourth capacitors each include a 0.1 μ F capacitor connected in series with a 2200 nF capacitor.

10. The power conversion system of claim 1, further comprising an enclosure with a first cabinet that houses the rectifier and the inverter, and a second cabinet that houses the filter.

11. A filter, comprising:

- a filter input, including a plurality of filter input terminals;
- a filter output, including a plurality of filter output terminals;
- a plurality of conductive busbars individually including a first end connected to a corresponding one of the plurality of filter input terminals, and a second end connected to a corresponding one of the plurality of filter output terminals;
- a first capacitor circuit, including a plurality of first capacitors individually coupled between a first common connection and a corresponding one of the busbars at a first location proximate the plurality of filter input terminals;
- a first inductor circuit, including a plurality of first common mode cores that individually extend around the plurality of busbars at a second location between the first location and the second end of the busbars;
- a second capacitor circuit, including a plurality of second capacitors individually coupled between a second common connection and a corresponding one of the busbars at a third location between the second location and the second end of the busbars;
- a second inductor circuit, including a plurality of second common mode cores that individually extend around the busbars at a fourth location between the third location and the second end of the busbars;
- a third capacitor circuit, including a plurality of third capacitors individually coupled between a third common connection and a corresponding one of the busbars

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at a fifth location between the fourth location and the second end of the busbars; and
 a fourth capacitor circuit, including a plurality of fourth capacitors individually coupled between a fourth common connection and a corresponding one of the busbars at the fifth location.

12. The filter of claim **11**, wherein the second, third, and fourth common connections each coupled to a common reference node.

13. The filter of claim **12**, wherein the second capacitor circuit includes a second grounding capacitor connected between the second common connection and the common reference node; wherein the third capacitor circuit includes a third grounding capacitor connected between the third common connection and the common reference node; and wherein the fourth capacitor circuit includes a fourth grounding capacitor connected between the fourth common connection and the common reference node.

14. The filter of claim **12**, wherein the first common mode cores and the second common mode cores include a nanocrystalline material.

15. The filter of claim **12**, wherein the first capacitor circuit, the first inductor circuit, the second capacitor circuit, the second inductor circuit, and the third capacitor circuit form a band stop filter

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with a cut-in frequency of 150 kHz or less, and a cut-off frequency of 3 MHz to 10 MHz; and wherein the fourth capacitor circuit forms a low pass filter with a cutoff frequency of 3 MHz to 10 MHz.

16. The filter of claim **11**, wherein the first common mode cores and the second common mode cores include a nanocrystalline material.

17. The filter of claim **11**, wherein the first capacitor circuit, the first inductor circuit, the second capacitor circuit, the second inductor circuit, and the third capacitor circuit form a band stop filter with a cut-in frequency of 150 kHz or less, and a cut-off frequency of 3 MHz to 10 MHz; and wherein the fourth capacitor circuit forms a low pass filter with a cutoff frequency of 3 MHz to 10 MHz.

18. The filter of claim **17**, wherein the first capacitors, the second capacitors, and the third capacitors have capacitance values of 4.7 μF .

19. The filter of claim **18**, wherein the individual fourth capacitors each include a 0.1 μF capacitor connected in series with a 2200 nF capacitor.

20. The filter of claim **17**, wherein the first common mode cores and the second common mode cores include a nanocrystalline material.

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